ELASTIC DEFORMATION / FORCE RATIO OF SELECTED FINGER SPRINGS USED IN REMOVABEL ORTHODONTIC APPLIANCES.

By

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INTRODUCTION

Finger springs are incorporated into removable acrylic appliances to achieve tooth tipping movement. These appliances are widely used in general dentistry, pedodontics, and, to a lesser degree, in orthodontics. The ease of construction and limited chair time make these appliances useful in cases where it is necessary to regain lost space or correct minor anterior crossbites.

Selection of spring design and wire diameter is quite often arbitrary. Guidelines which may give the clinician a foundation for this selection should be based on the efficiency of a spring in applying a uniform force over the entire distance of tooth movement. This property of a spring is best described by the elastic deformation/force ratio, which is a measure of the elastic deformation that occurs under a given force load within the confines of the elastic limit.[1] A higher ratio implies less loss of force during the deflection of a spring and would, therefore, be a desirable property for finger springs. An example might serve to explain this property further:

Spring A has an elastic deformation/force ratio (mm/100 grams) of 6. Spring B has a ratio of 3.

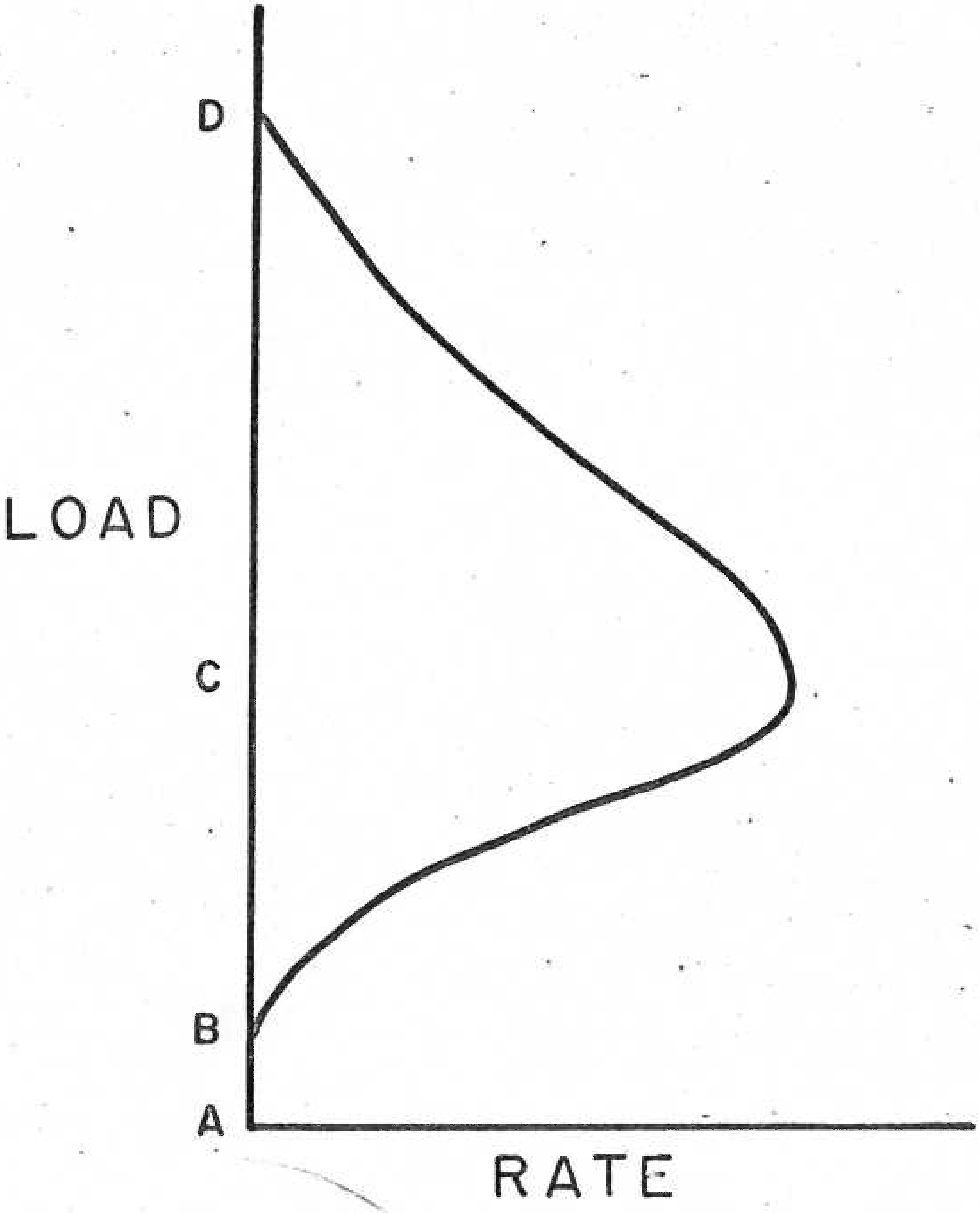
Spring A must be activated 6 mm to exert a reciprocal force of 100 grams, while spring B must only be activated 3 mm to achieve the same reciprocal force. After spring A has been in use and has been deactivated (or tipped a tooth) 2 mm, it exerts a force of 66 grams. With the same amount of deactivation, spring B exerts only 33 grams of force. The spring with the higher elastic deformation/force ratio has acted over the same distance with a smaller loss of force.

The purpose of this investigation was to quantitate the elastic deformation/force ratio for various finger springs, in order to determine the magnitude of differences which may exist as a function of spring design and wire diameter. This information may then provide the clinician with a more rational basis for making comparisons of finger springs for a given situation where range of movement and amount of force would be two of the considerations. In addition, this investigation was designed to evaluate the variability in the elastic deformation/force ratio of hand formed springs in comparison to machine formed springs. An assumption was made that machine formed springs would have minimal variation and, therefore, could be used as a standard to evaluate the variation in mechanical properties of hand formed springs.

springs. From the results of this study, Storey and Smith proposed a theory of optimal force which is represented in Fig. 1. They concluded that there is a threshold force, point B, below which movement of teeth will not occur. As the force increases, the rate of tooth movement increases until it reaches a maximum rate, point C. This is the point of optimal force. An increase beyond the optimal force will result in a decrease in the rate of tooth movement until a point is reached, point D, where tooth movement ceases. Increasing the force beyond point D will result in movement of anchor teeth.

The theory of optimal force has been questioned by Hixon et al.[3] They reported a study of cuspid retraction in eight patients over a period of eight weeks. A 300 gram continuous force was applied to the right maxillary and mandibular cuspids of all patients. The cuspids on the left side of five patients received differing continuous forces ranging from 64 to 1515 grams. The left cuspids of three patients received initial forces ranging from 175 to 900 grams, but these forces were allowed to decay. The retraction springs were activated at biweekly intervals in an attempt to maintain continuous forces. Measurements of tooth movement were made from biweekly study casts and from pre-treatment and post-treatment modified cephalometric films, with tantalum implants

Fig. 1. Relationship between force and rate of tooth movement during cuspid retraction. A. Force below threshold. B. Threshold force. C. Optimal force. D. Maximum force. (From Storey, E., and Smith, R. Austral. J. Dent., 56:11-8, Feb. 1952)


D
LOAD
C
B
A
RATE

serving as fixed reference points. The results of this study indicate the extreme variation in tooth movement between individuals, and they do not support the concept of optimal force. A conclusion was drawn that heavier forces per unit area of root surface increase the rate of tooth movement, at least up to approximately 300 grams. Rapid tooth movement which is clinically evident with much lighter forces was explained as a result of tooth tipping movement rather than bodily translation. Apparent rapid tooth movement may merely reflect crown displacement during tipping. The forces of tipping movement place a high load at the alveolar crest and may result in some amount of bone deformation in this area.

Weinstein[4] was concerned with the minimal forces which would produce tooth movement. He reported a series of experiments designed to measure the forces exerted on the dentition by the buccinator muscle and to determine the effect of these forces on tooth position. It was found that the cheek musculature exerted a mean resting force of approximately 5 grams on the mandibular first bicuspids. Gold inlays inserted on the buccal surfaces of first bicuspids were made to extrude 2 mm from the tooth surface, thereby distending the cheek. The reciprocal force exerted by the cheek was determined to be approximately 2 grams. This small amount of additional force was sufficient to cause movement of the teeth over a period of time.

Burstone and Groves[5] have shown that the most rapid rates of tooth movement occurred in the retraction of anterior teeth after the application of 50 to 75 grams of force. Their study employed helical tension springs in the treatment of twenty-two patients with a mean age of nine years. They found no increase in the rate of tooth movement with an increase in force. They were not able to demonstrate a threshold value for anterior teeth.

The pattern of tooth movement has been the subject of several investigations to determine whether movement is continuous or intermittent. Reitan[6] described a lag phase following the initial movement of a tooth, corresponding to a histologic picture of hyalinization. He recommended the use of light forces during the initial stages of tooth movement. Light forces tend to form cell-free hyalinized areas which are less extensive and are more readily eliminated by the resorptive process. Heavy forces tend to create new areas of hyalinization as soon as the initial areas have been resorbed, thus impeding tooth movement. An initial force of 25 to 40 grams was recommended for continuous tipping movement during the initial stages. During the final stages of continuous bodily movement, the forces may vary with root length; maxillary cuspids may require 150 to 250 grams, while mandibular cuspids may require

100 to 200 grams.

Burstone[7] has supported Reitan's concept of the lag phase during tooth movement and has pointed out the complexity of the relationship between force magnitude and rate of tooth movement. He stated that lighter forces move teeth more gradually and that an increase in force magnitude will increase the rate of tooth movement. Heavier forces were said to result in a hyalinization of the periodontal membrane and to result in an increased lag phase.

Hixon et al[3] demonstrated that a continuous force of 300 grams produced a three week lag after initial movement of a cuspid in one patient. After the lag period, relatively continuous movement began at a rate of approximately 0.4 mm per week. A 64 gram force applied to retract another cuspid in the same patient resulted in no movement during the first month. After this period of time, movement began at a rate of approximately 0.1 mm per week. These findings demonstrate the inconsistency of the rate of tooth movement.

It becomes apparent from these studies that the theory of optimal force is open to question. It has been shown that both heavy and light forces are capable of producing rapid tooth movement. The rate of movement, therefore, may not be a valid indication of optimal force.[7] If an optimal force does exist, there is no method currently available to determine the magnitude of this force prior to treatment because of the wide range of individual variation in response to tooth movement forces.[3]

Burstone et al[8] presented a comprehensive report of the biomechanical principles involved in the application of light continuous forces. An understanding of the force systems involved in tooth movement is dependent on the magnitude and direction of the force, its point of application, the distance over which the force acts, and the uniformity of the force throughout this distance. The ideal orthodontic spring should possess the ability to release a constant force throughout the range of tooth movement. The most constant forces are produced by springs which have low load-deflection rates. An effective method of lowering the load-deflection rate is to incorporate additional wire into the spring in the form of helices placed where the bending moment is maximal. This will allow a marked reduction in the load-deflection rate without appreciably altering the ability of the spring to withstand permanent deformation. The rate may also be substantially lowered by reducing the cross-sectional dimension of the wire.

Mahler and Goodwin[1] described the elastic deformation/force ratio as a mechanical property of orthodontic springs which has important clinical significance. The ratio was expressed in mm/100 grams, which allows for ease of interpretation and application to clinical usage. The ratio describes the elastic deformation which occurs in a wire under a given load, as well as the decrease in applied force which occurs as a wire or spring is deactivated by tooth movement. Their study was designed to determine the elastic deformation/force ratio and elastic limit of different types of small diameter wire springs. Four different designs of springs were hand formed from seven different types of wire. Comparisons were made between heat treated and non-heat treated springs. It was concluded that spring design had a significant influence on the properties tested. Heat treatment resulted in the undesirable effect of lowering the elastic deformation/force ratio. There was no evidence to indicate the superiority of one type of wire over another type. The elastic limits of all springs tested were higher than forces which are likely to be encountered in clinical usage.

MATERIALS AND METHODS

The wire used in this investigation was an 18-8 austenitic stainless steel round wire, type 302, which is commercially available for orthodontic purposes.* Three different spring designs commonly used in removable appliance therapy were tested (Fig. 2). Springs of each design were fabricated from .018, .022, .025, and .030 inch wire. For every combination of spring design and wire diameter, five samples were formed by hand and five samples were formed by machine.

The wire was received in fourteen inch lengths. For convenience in handling, the wire was placed in a cutting quill with a .040 inch round aperture and cut into two inch sections on a foot press.** These sections were then used to fabricate the various springs.

The hand formed springs were made by the same operator using a #139 wire bending plier. The order in which these springs were formed, with regard to design and wire diameter, was intended to be impartial, although random number tables

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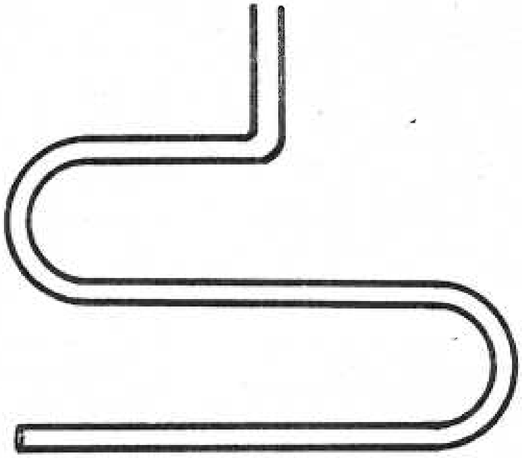
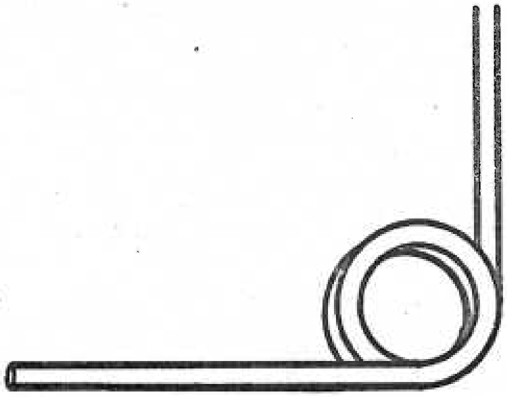
* Tru-Chrome, Rocky Mountain Dental Products Co., Denver, Colo.

** Royersford Foundry and Machine Co., Royersford, Pa.

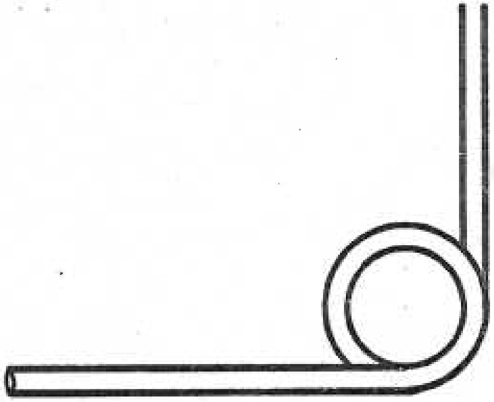
Fig. 2. Finger spring designs. I. Single helix. II. Double helix. III. S-shape, no helix.



III



II



I

were not used. An effort was made to form the springs as nearly alike as possible. Approximately half of the total samples were formed on separate days, but no attempt was made to record this time element.

The machine formed springs were wound on a foot press coiler. The 90 degree bend in spring design III was placed by using a pin die and forming punch in a foot press. In the interest of time and economy, and because minimum variation was expected in machine formed samples of the same design and diameter, there was an ordered sequence in the fabrication of these springs.

The springs were placed in a tensile testing instrument* which records force-deformation curves. The springs were supported in a pin vise which was adjusted laterally to position the loading point 5.0 mm from the outside edge of the coils (Fig. 3). With the aid of a 0.25 mm metal shim, the springs were placed at a constant height in the pin vise. The force was delivered vertically through a hollow aluminum loading pin weighing 11.4 grams. A 10 mm section of .040 inch round wire was attached horizontally to the tip of the loading pin (Fig. 3). This section of wire allowed more precise

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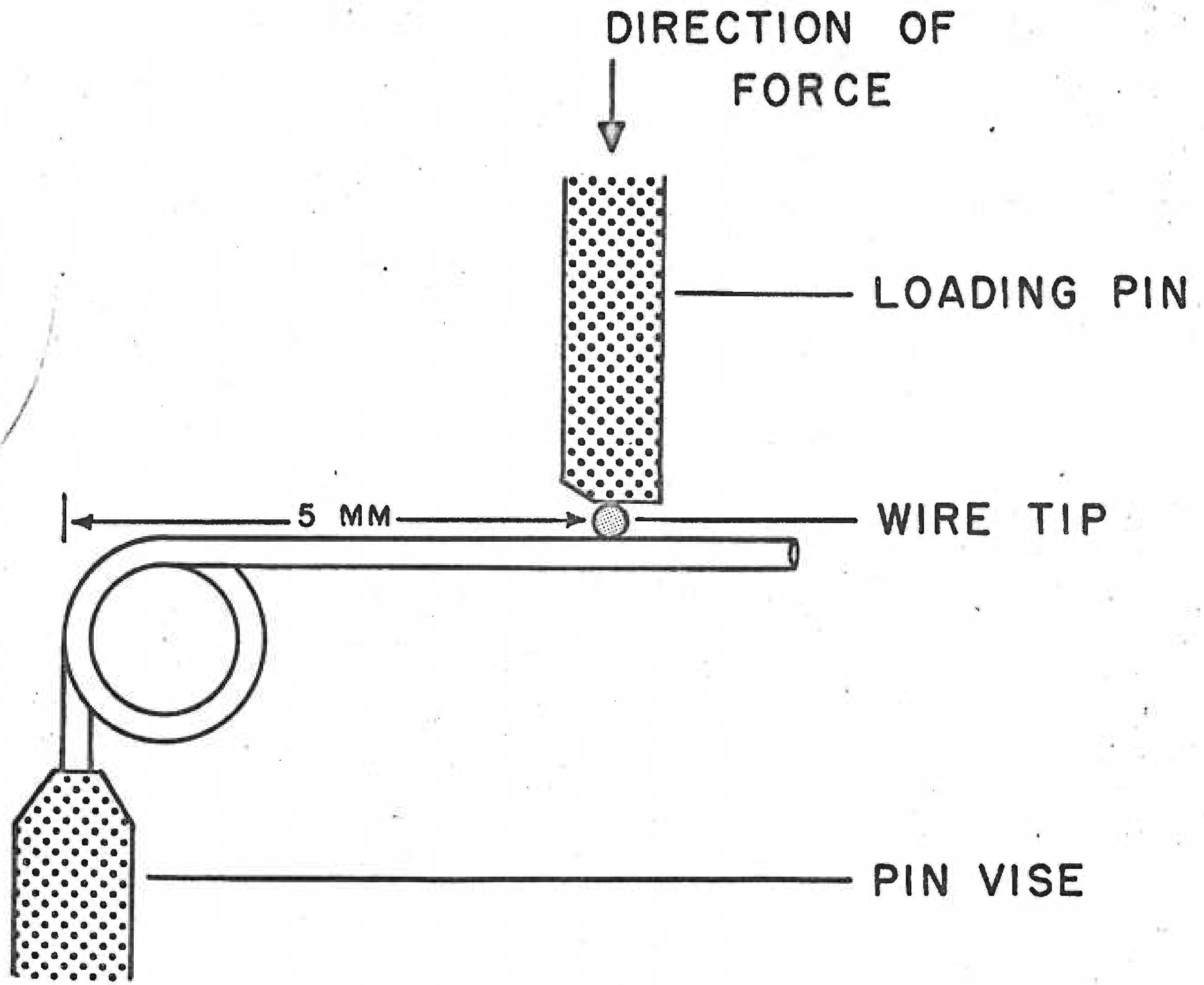
* Instron Engineering Corp., Canton, Mass.

Fig. 3. Spring positioned in testing instrument. The wire tip attached to the loading pin locates the loading point 5.0 mm from the outside edge of the helix.


DIRECTION OF
FORCE
LOADING PIN
5 MM
WIRE TIP
PIN VISE

control of the point of contact between the loading pin and the spring, and was also an effort to minimize friction surface area. The springs were loaded in a direction which tended to close the helix.

The slopes of the curves recorded by the testing instrument were visually determined and drawn on transpatent acetate overlays.* A sample chart recording is shown in Fig. 4. The order of the tracings was arbitrary. There were three repetitions of each tracing, made on three separate days. Elastic deformation/force measurements, expressed as mm/100 grams, were taken from the tracings. These measurements were also made on three separate days.

The data was subjected to a three factor analysis of variance, and Scheffé's method was used for paired contrasts. In an attempt to compensate for an anticipated violation of homogeneity of variance, the sample size was kept equal for all cells.[9,10,11] In addition, the 1% level was selected for statistical significance for each test.

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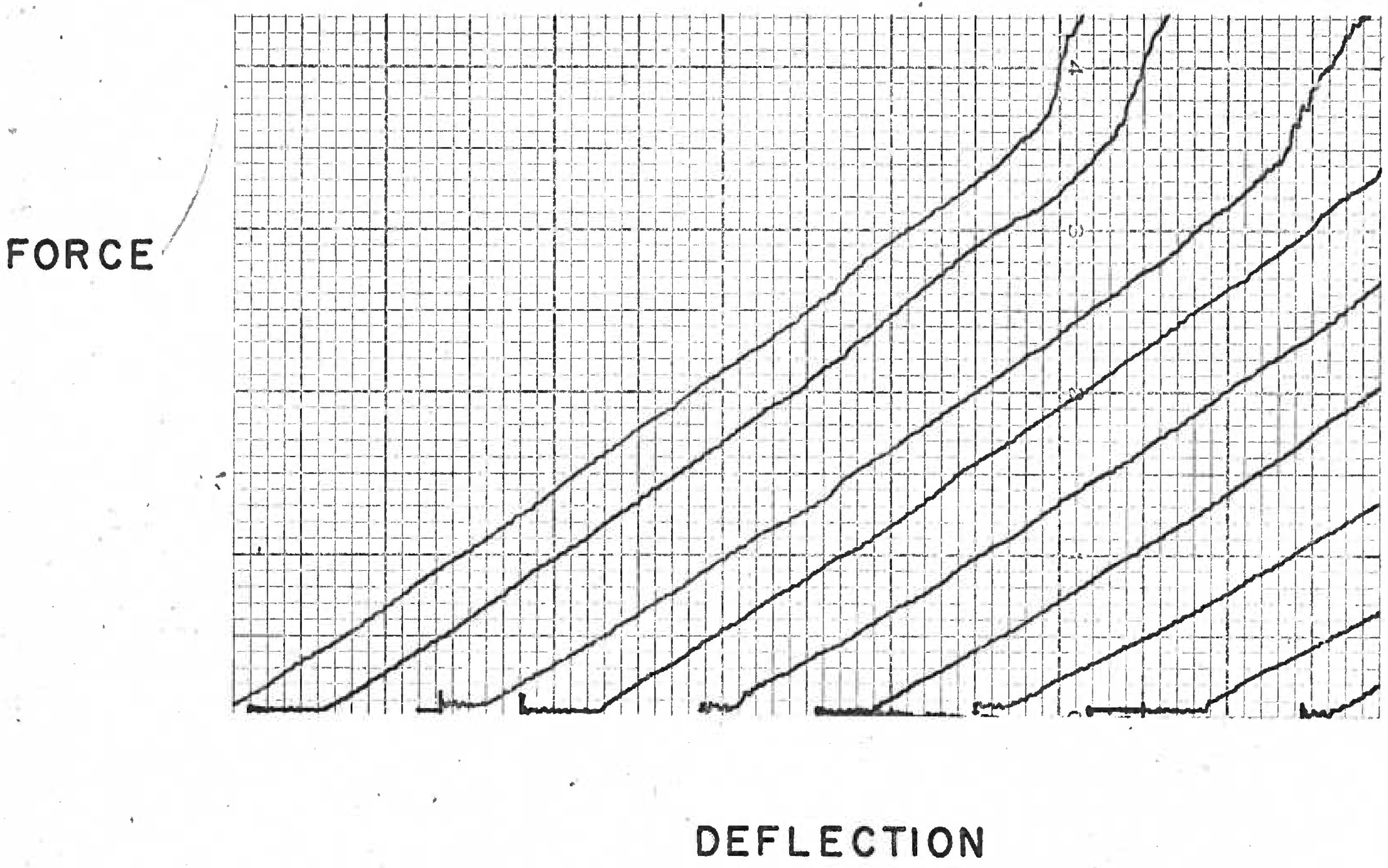
* Tuffilm, M. Grumbacher Inc., New York, N.Y.

Fig. 4. Chart recording of a force-deformation curve.


FORCE
DEFLECTION
4
3
2
1
0

RESULTS

There was a statistically significant interaction between spring design and wire diameter for the springs tested in this study. Comparing springs of the same design and wire diameter, the analysis of variance indicates that there was no statistical difference between the hand formed or the machine formed springs (Table I).

The mean elastic deformation/force ratios for various combinations of spring design and wire diameter are represented in Fig. 5. Each value is the mean ratio of five hand formed and five machine formed springs. Within each spring design tested, the ratios increased with the smaller wire diameters. Within each wire diameter tested, design II had the highest ratio and design III had the lowest ratio.

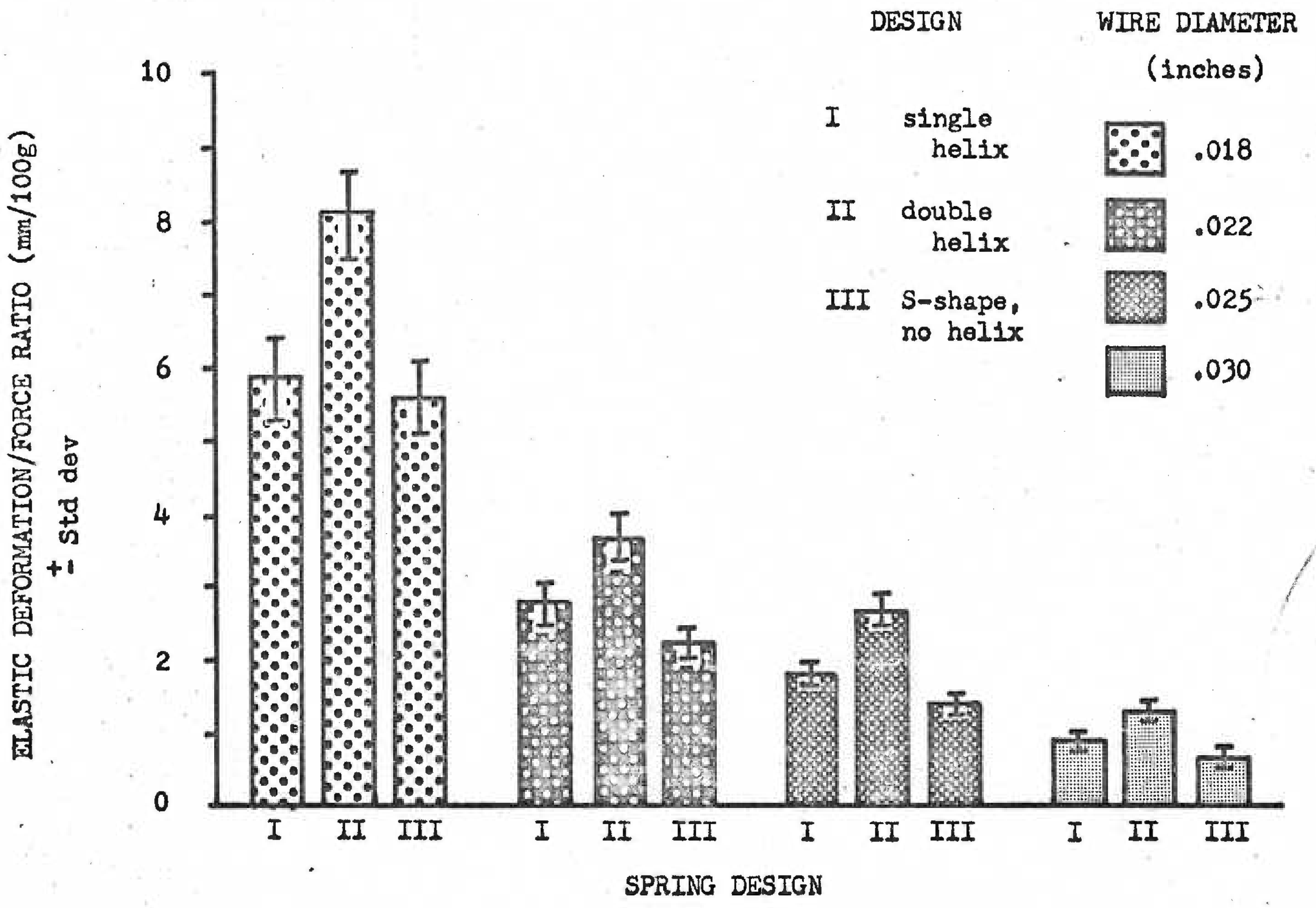
There were sixty-six possible paired contrasts for the twelve mean elastic deformation/force ratios obtained. Any pair of means that differ by more than 0.716 are statistically different by Scheffé's method. Fig. 6 represents ranked mean values of elastic deformation/force ratios and indicates those means which do not differ significantly. If one wished to fabricate a finger spring with an elastic deformation/force ratio of approximately 3 mm/100 grams, it would become evident

TABLE I. ANALYSIS OF VARIANCE SUMMARY TABLE

SOURCE	SS	DF	MS	F	
Design	139.626	2	69.813	245.358	Significant
Method	1.407	1	1.407	4.951	
Diameter	1701.495	3	529.764	1861.837	Significant
Design x Method	0.069	2	0.033	0.126	
Design x Diameter	35.079	6	5.844	20.547	Significant
Method x Diameter	1.161	3	0.387	1.360	
Design x Method x Diameter	3.324	6	0.552	1.947	
Error	27.315	96	0.282		
Measurement	0.299	240	0.001		
Total	1909.775	359			

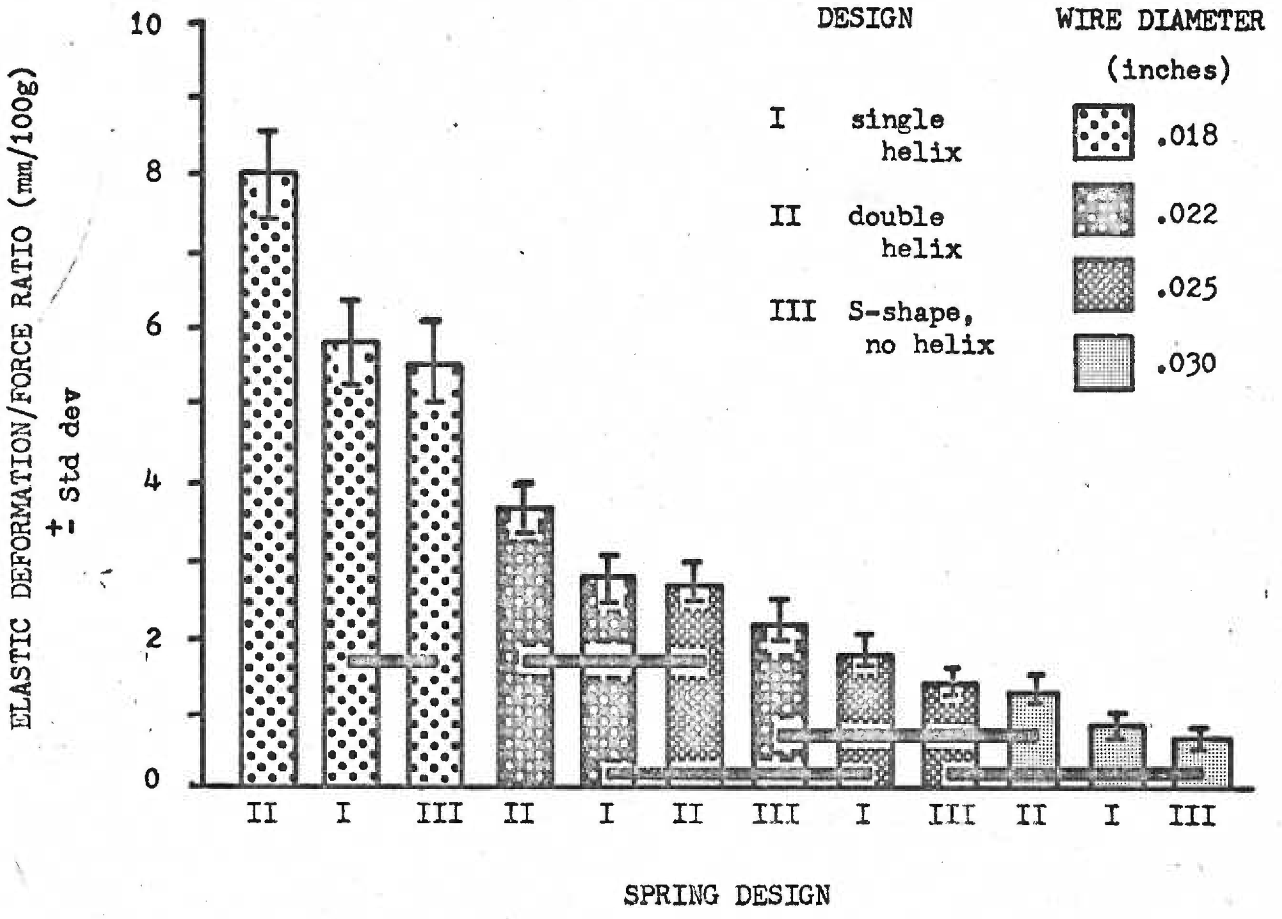
Note: The 1% level was selected for significant F values.

Fig. 5. Mean elastic deformation/force ratio for springs of different design and different wire diameter.



ELASTIC DEFORMATION/FORCE RATIO (mm/100g) ± Std dev
10
8
6
4
2
0
I
II
III
I
II
III
I
II
III
I
II
III
SPRING DESIGN
DESIGN
I single helix
II double helix
III S-shape, no helix
WIRE DIAMETER (inches)
.018
.022
.025
.030

Fig. 6. Ranked mean values of elastic deformation/force ratios. All means that are joined by a common line do not differ significantly at the 1% level.


ELASTIC DEFORMATION/FORCE RATIO (mm/100g)
± Std dev
10
8
6
4
2
0
II
I
III
II
I
II
III
I
III
II
I
III
SPRING DESIGN
DESIGN
I single helix
II double helix
III S-shape, no helix
WIRE DIAMETER
(inches)
.018
.022
.025
.030

from Fig. 6 that there would be no significant difference between springs of design I - .022 inch wire, design II - .022 inch wire, or design II - .025 inch wire. Any of these springs would provide essentially the same force when deflected a given distance, and all would have essentially the same rate of force decay throughout the range of movement. Similar comparisons can be made for other chosen elastic deformation/force ratios.

DISCUSSION

The elastic deformation/force ratio provides the clinician with the ability to compare springs on a rational basis in search for one that will provide the most uniform force throughout the distance of tooth movement.

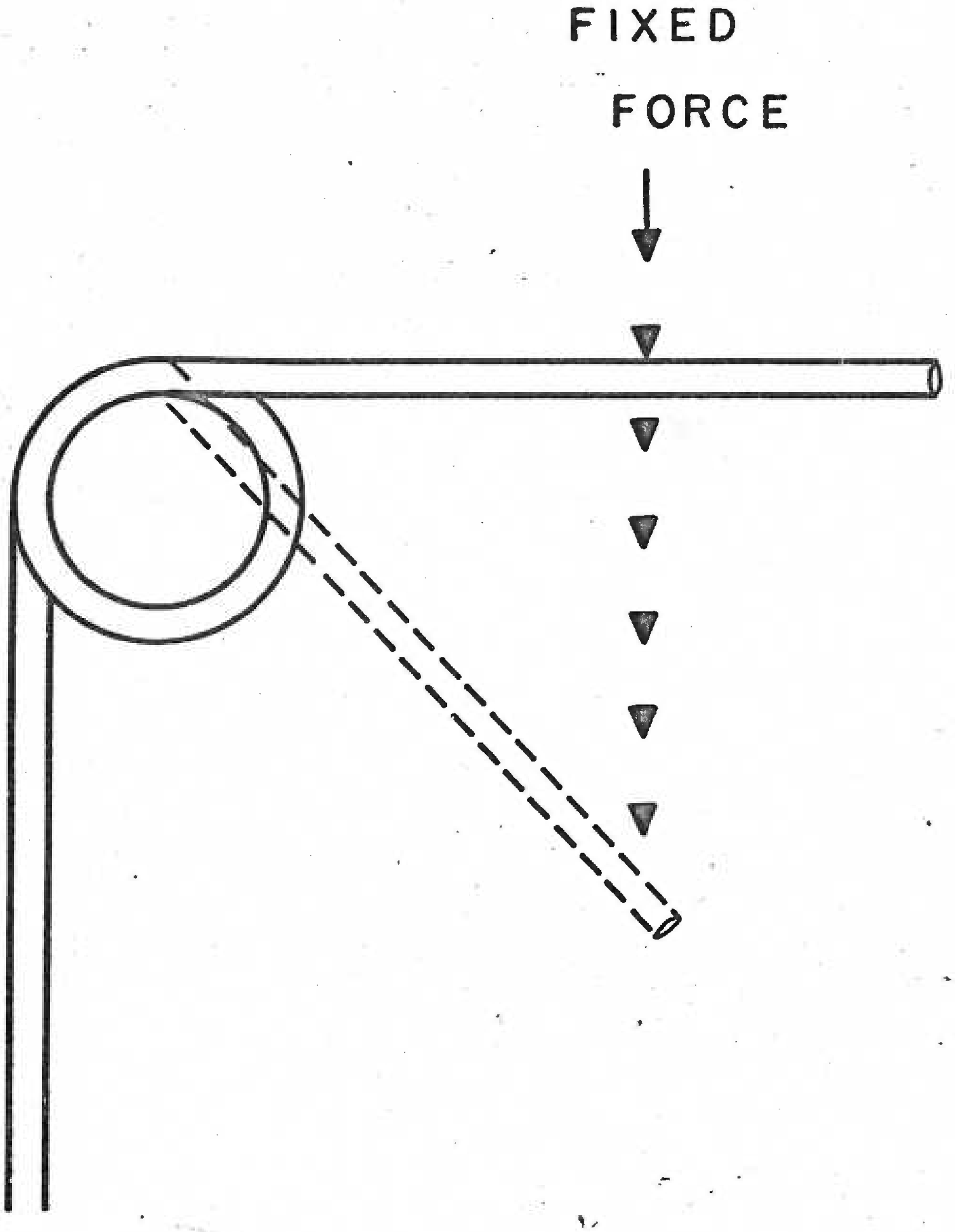
Spring design and wire diameter are two factors which are effective in altering the mechanical properties of a spring. The finger spring is basically a cantilever beam system wherein the beam is supported at one end and receives a load on the non-supported end. The deflection of a cantilever beam is a cubic function of its length. The springs in this study had an effective beam length of 5 mm. If this length were doubled, the deflection would be eight times as great. Thus, it can be assumed that an increase in beam length would show a dramatic increase in the elastic deformation/force ratio.

Placement of one or more helices adjacent to the supported end of the cantilever beam has been advocated by Burstone and co-workers[8] as a method which would increase the elastic deformation/force ratio without reducing the elastic limit. (They report in terms of spring rate and allowable load. Spring rate is the inverse of elastic deformation/force. Allowable load is equivalent to elastic limit.) They have also shown that a higher elastic deformation/force ratio can be expected from springs that are activated in the same direction as the original bending of the helix.

The elastic deformation/force ratio is inversely proportional to the fourth power of the wire diameter. Although decreasing the wire diameter is an effective method of increasing this ratio, care must be taken not to select a wire that will be easily distorted or that requires an excessive amount of activation to provide a desired amount of force.

According to Hooke's law, the force-deformation "curve" is ideally plotted as a straight line. A representative force-deformation recording from this investigation is shown in Fig. 4. This "curve" can be seen to deviate from a straight line. This may be the result of several phenomena occurring simultaneously: 1) A change in the length of the cantilever beam during loading. The position of the loading pin was fixed vertically as the beam was deflected in an arc, thereby increasing the effective length of the beam (Fig. 7). 2) A change in the direction of force. The initial force was applied in a vertical direction but, as the beam was deflected in an arc, a horizontal component of force was introduced. 3) A change in the shape of the spring may have

Fig. 7. Spring deflection pattern. As a finger spring is deflected in an arc by a fixed vertical force, the length of the cantilever beam is increased.


FIXED
FORCE

occurred during deflection. Lighter wires would appear to be affected more by these three phenomena because of their greater deflection under a given load.

In this study there was no significant difference in elastic deformation/force ratios between hand formed or machine formed springs of the same design and wire diameter. With careful attention to detail, a clinician can fabricate finger springs that will have elastic deformation/force ratios which are consistently similar.

The springs tested in this study were not subjected to heat treatment. Principles of metallurgy dictate that cold worked stainless steel wires should be heat treated to relieve internal stresses.[13,14,15] However, it is not felt that this is a necessary procedure for finger springs designed for minor tooth movement, nor is it, in reality, a common procedure in clinical usage. It is known that heat treatment will increase the elastic limit of a wire or spring, but the forces required of finger springs are not normally expected to exceed the elastic limit. It has also been shown that heat treatment may have the disadvantage of lowering the elastic deformation/force ratio.[1]

This study was not intended to recommend a specific design or diameter of finger spring, nor an optimal elastic deformation/force ratio. It was designed to quantitate a clinically meaningful property of selected finger springs, in an effort to gain a better understanding of the force systems involved in removable appliance therapy. The biologic variation in tooth movement can only be studied adequately after the mechanical variables are understood and controlled.[3]

SUMMARY AND CONCLUSIONS

Elastic deformation/force ratios were determined for various designs and wire diameters of finger springs. A comparison of this ratio was made between springs which were formed by hand and springs which were formed by machine. The following conclusions have been drawn from the results of this study:

1) Wire diameter has a greater influence than spring design on elastic deformation/force ratios. The ratio increases inversely to increased wire diameter.
2) Spring design significantly influences elastic deformation/force ratios. One or more helices placed near the supported end of the spring increases the ratio.
3) There is no significant difference in elastic deformation/force ratios between hand formed or machine formed springs.
4) Various spring designs and wire diameters may be combined to produce finger springs with selected elastic deformation/force ratios.

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APPENDIX

TABLE A. SLOPE MEASUREMENTS TRANSFORMED TO ELASTIC DEFORMATION/FORCE RATIOS FOR .018 INCH SPRINGS

DESIGN	METHOD OF FABRICATION	SAMPLE	REPETITIONS (mm)			TRANSFORMATIONS (mm/100g)			$\bar{X}$ (mm/100g)
			1	2	3	1	2	3	
I	Hand	1	543	544	542	5.980	5.991	5.969	5.980
		2	635	640	639	6.993	7.048	7.037	7.026
		3	493	489	496	5.429	5.385	5.462	5.425
		4	526	523	526	5.792	5.759	5.792	5.781
		5	556	550	557	6.123	6.057	6.134	6.104
I	Machine	1	568	579	575	6.255	6.376	6.332	6.321
		2	543	542	533	5.980	5.969	5.870	5.939
		3	475	468	465	5.231	5.154	5.121	5.168
		4	532	528	522	5.859	5.814	5.748	5.807
		5	526	522	518	5.792	5.748	5.704	5.748

TABLE B. SLOPE MEASUREMENTS TRANSFORMED TO ELASTIC DEFORMATION/FORCE RATIOS FOR .018 INCH SPRINGS

DESIGN	METHOD OF FABRICATION	SAMPLE	REPETITIONS (mm)			TRANSFORMATIONS (mm/100g)			$\bar{X}$ (mm/100g)
			1	2	3	1	2	3	
II	Hand	1	735	735	738	8.094	8.094	8.127	8.105
		2	645	645	655	7.103	7.103	7.213	7.140
		3	702	696	697	7.731	7.665	7.676	7.690
		4	794	791	805	8.744	8.711	8.865	8.773
		5	785	786	772	8.645	8.656	8.502	8.601
II	Machine	1	698	688	688	7.687	7.577	7.577	7.613
		2	742	735	739	8.171	8.094	8.138	8.135
		3	735	742	745	8.094	8.171	8.204	8.157
		4	801	805	803	8.821	8.865	8.843	8.843
		5	726	728	728	7.995	8.017	8.017	8.010

TABLE C. SLOPE MEASUREMENTS TRANSFORMED TO ELASTIC DEFORMATION/FORCE RATIOS FOR .018 INCH SPRINGS

DESIGN	METHOD OF FABRICATION	SAMPLE	REPETITIONS (mm)			TRANSFORMATIONS (mm/100g)			$\bar{X}$ (mm/100g)
			1	2	3	1	2	3	
III	Hand	1	547	546	544	6.024	6.013	5.991	6.009
		2	473	479	478	5.209	5.275	5.264	5.249
		3	565	562	562	6.222	6.189	6.189	6.200
		4	534	525	525	5.881	5.781	5.781	5.814
		5	643	642	642	7.081	7.070	7.070	7.074
III	Machine	1	499	489	487	5.495	5.385	5.363	5.414
		2	462	465	464	5.088	5.121	5.110	5.106
		3	458	455	458	5.044	5.011	5.044	5.033
		4	481	497	485	5.297	5.473	5.341	5.370
		5	500	502	497	5.506	5.528	5.473	5.502

TABLE D. SLOPE MEASUREMENTS TRANSFORMED TO ELASTIC DEFORMATION/FORCE RATIOS FOR .022 INCH SPRINGS

DESIGN	METHOD OF FABRICATION	SAMPLE	REPETITIONS (mm) 1	2	3	TRANSFORMATIONS (mm/100g) 1	2	3	$\bar{X}$ (mm/100g)
I	Hand	1	269	270	265	2.962	2.973	2.918	2.951
		2	244	240	243	2.687	2.643	2.676	2.668
		3	239	243	242	2.632	2.676	2.665	2.657
		4	266	268	267	2.929	2.951	2.940	2.940
		5	297	303	298	3.270	3.337	3.281	3.296
I	Machine	1	249	246	245	2.742	2.709	2.698	2.716
		2	244	245	242	2.687	2.698	2.665	2.683
		3	264	262	262	2.907	2.885	2.885	2.892
		4	290	290	290	3.193	3.193	3.193	3.193
		5	239	235	236	2.632	2.588	2.599	2.606

TABLE E. SLOPE MEASUREMENTS TRANSFORMED TO ELASTIC
DEFORMATION/FORCE RATIOS FOR .022 INCH SPRINGS

DESIGN	METHOD OF FABRICATION	SAMPLE	REPETITIONS (mm)			TRANSFORMATIONS (mm/100g)			$\bar{X}$ (mm/100g)
			1	2	3	1	2	3	
II	Hand	1	362	359	363	3.986	3.953	3.997	3.979
		2	383	382	382	4.218	4.207	4.207	4.210
		3	369	367	364	4.063	4.041	4.008	4.038
		4	321	320	323	3.535	3.524	3.557	3.538
		5	315	314	316	3.469	3.458	3.480	3.469
II	Machine	1	356	355	355	3.920	3.909	3.909	3.913
		2	355	357	355	3.909	3.931	3.909	3.917
		3	287	285	285	3.160	3.138	3.138	3.146
		4	359	360	359	3.953	3.964	3.953	3.957
		5	323	323	324	3.557	3.557	3.568	3.560

TABLE F. SLOPE MEASUREMENTS TRANSFORMED TO ELASTIC DEFORMATION/FORCE RATIOS FOR .022 INCH SPRINGS

DESIGN	METHOD OF FABRICATION	SAMPLE	REPETITIONS (mm) 1	2	3	TRANSFORMATIONS (mm/100g) 1	2	3	$\bar{X}$ (mm/100g)
III	Hand	1	184	185	186	2.026	2.037	2.048	2.037
		2	219	223	221	2.411	2.455	2.433	2.433
		3	240	242	240	2.643	2.665	2.643	2.650
		4	215	214	219	2.367	2.356	2.411	2.378
		5	172	172	171	1.894	1.894	1.883	1.890
III	Machine	1	209	206	210	2.301	2.268	2.312	2.294
		2	202	201	200	2.224	2.213	2.202	2.213
		3	210	209	211	2.132	2.301	2.323	2.312
		4	196	191	194	2.158	2.103	2.136	2.132
		5	213	215	216	2.345	2.367	2.378	2.364

TABLE G. SLOPE MEASUREMENTS TRANSFORMED TO ELASTIC DEFORMATION/FORCE RATIOS FOR .025 INCH SPRINGS

DESIGN	METHOD OF FABRICATION	SAMPLE	REPETITIONS (mm)			TRANSFORMATIONS (mm/100g)			$\bar{X}$ (mm/100g)
			1	2	3	1	2	3	
I	Hand	1	186	185	183	2.048	2.037	2.015	2.033
		2	166	164	171	1.828	1.806	1.883	1.839
		3	163	167	165	1.795	1.839	1.817	1.817
		4	169	168	168	1.861	1.850	1.850	1.853
		5	156	154	156	1.718	1.696	1.718	1.710
I	Machine	1	167	169	168	1.839	1.861	1.850	1.850
		2	169	169	169	1.861	1.861	1.861	1.861
		3	158	162	158	1.740	1.784	1.740	1.754
		4	154	153	153	1.696	1.685	1.685	1.688
		5	158	160	158	1.740	1.762	1.740	1.747

TABLE H. SLOPE MEASUREMENTS TRANSFORMED TO ELASTIC DEFORMATION/FORCE RATIOS FOR .025 INCH SPRINGS

DESIGN	METHOD OF FABRICATION	SAMPLE	REPETITIONS (mm)			TRANSFORMATIONS (mm/100g)			$\bar{X}$ (mm/100g)
			1	2	3	1	2	3	
II	Hand	1	214	210	215	2.356	2.312	2.367	2.345
		2	264	265	270	2.907	2.918	2.973	2.933
		3	278	277	279	3.061	3.050	3.072	3.061
		4	259	257	260	2.852	2.830	2.863	2.848
		5	271	265	272	2.984	2.918	2.995	2.966
II	Machine	1	235	239	240	2.588	2.632	2.643	2.621
		2	246	252	249	2.709	2.775	2.742	2.742
		3	260	254	256	2.863	2.797	2.819	2.826
		4	227	233	230	2.500	2.566	2.533	2.533
		5	238	238	240	2.621	2.621	2.643	2.628

TABLE I. SLOPE MEASUREMENTS TRANSFORMED TO ELASTIC DEFORMATION/FORCE RATIOS FOR .025 INCH SPRINGS

DESIGN	METHOD OF FABRICATION	SAMPLE	REPETITIONS (mm)			TRANSFORMATIONS (mm/100g)			$\overline{X}$ (mm/100g)
			1	2	3	1	2	3	
III	Hand	1	120	116	118	1.321	1.277	1.299	1.299
		2	133	133	133	1.464	1.464	1.464	1.464
		3	120	121	120	1.321	1.332	1.321	1.325
		4	115	112	111	1.266	1.233	1.222	1.240
		5	146	144	146	1.607	1.585	1.607	1.600
III	Machine	1	133	133	136	1.464	1.464	1.497	1.475
		2	138	140	135	1.519	1.541	1.486	1.516
		3	135	137	134	1.486	1.508	1.475	1.490
		4	130	131	129	1.431	1.442	1.420	1.431
		5	137	135	136	1.508	1.486	1.497	1.497

TABLE J. SLOPE MEASUREMENTS TRANSFORMED TO ELASTIC DEFORMATION/FORCE RATIOS FOR .030 INCH SPRINGS

DESIGN	METHOD OF FABRICATION	SAMPLE	REPETITIONS (mm) 1	2	3	TRANSFORMATIONS (mm/100g) 1	2	3	$\bar{X}$ (mm/100g)
I	Hand	1	087	089	088	0.958	0.980	0.969	0.969
		2	090	091	087	0.991	1.002	0.958	0.983
		3	081	079	079	0.892	0.870	0.870	0.877
		4	100	099	098	1.101	1.090	1.079	1.090
		5	094	090	088	1.035	0.991	0.969	0.998
I	Machine	1	087	086	085	0.958	0.947	0.936	0.947
		2	089	086	087	0.980	0.947	0.958	0.961
		3	085	085	084	0.936	0.936	0.925	0.932
		4	085	085	086	0.936	0.936	0.947	0.939
		5	087	087	088	0.958	0.958	0.969	0.961

TABLE K. SLOPE MEASUREMENTS TRANSFORMED TO ELASTIC DEFORMATION/FORCE RATIOS FOR .030 INCH SPRINGS

DESIGN	METHOD OF FABRICATION	SAMPLE	REPETITIONS (mm) 1	2	3	TRANSFORMATIONS (mm/100g) 1	2	3	$\overline{X}$(mm/100g)
II	Hand	1	132	131	131	1.453	1.442	1.442	1.446
		2	147	147	144	1.618	1.618	1.585	1.607
		3	118	119	118	1.299	1.310	1.299	1.303
		4	127	125	125	1.398	1.376	1.376	1.383
		5	123	122	124	1.354	1.343	1.365	1.354
II	Machine	1	122	123	123	1.343	1.354	1.354	1.350
		2	111	110	107	1.222	1.211	1.178	1.204
		3	122	115	119	1.343	1.266	1.310	1.306
		4	118	117	114	1.299	1.288	1.255	1.281
		5	100	104	097	1.101	1.145	1.068	1.104

TABLE L. SLOPE MEASUREMENTS TRANSFORMED TO ELASTIC DEFORMATION/FORCE RATIOS FOR .030 INCH SPRINGS

DESIGN	METHOD OF FABRICATION	SAMPLE	REPETITIONS (mm) 1	2	3	TRANSFORMATIONS (mm/100g) 1	2	3	$\overline{X}$ (mm/100g)
III	Hand	1	058	061	057	0.638	0.671	0.627	0.646
		2	067	066	068	0.737	0.726	0.748	0.737
		3	058	057	059	0.638	0.627	0.649	0.638
		4	066	067	067	0.726	0.737	0.737	0.734
		5	065	065	065	0.715	0.715	0.715	0.715
III	Machine	1	067	070	069	0.737	0.770	0.759	0.756
		2	065	064	066	0.715	0.704	0.726	0.715
		3	071	070	070	0.781	0.770	0.770	0.774
		4	064	063	064	0.704	0.693	0.704	0.701
		5	069	067	071	0.759	0.737	0.781	0.759

TABLE M. ELASTIC DEFORMATION/FORCE RATIO (mm/100g)
FOR SPRINGS OF DIFFERENT DESIGN AND DIFFERENT WIRE DIAMETER

DESIGN	DIAMETER	$\overline{X}$	S_p	CV(%)	SE_{meas}
I	.018	5.930	.567	9.56	.179
	.022	2.860	.248	8.68	.078
	.025	1.815	.097	5.36	.030
	.030	0.966	.054	5.64	.017
II	.018	8.107	.567	6.99	.179
	.022	3.773	.337	8.93	.106
	.025	2.750	.215	7.82	.068
	.030	1.334	.107	8.06	.034
III	.018	5.677	.491	8.66	.155
	.022	2.270	.227	10.02	.071
	.025	1.434	.105	7.33	.033
	.030	0.717	.040	5.68	.012

Note: Means that differ by more than 0.716 are significantly different by Scheffé's method ($p < .01$).